LARGE HADRON COLLIDER
LHC

ATLAS

Drawings

Reality
LHC SCHEDULE

Timeline
- Conception: ~1984
- Approval: 1994
- Start of Construction: 2000
- First Collisions: July 2008

Properties
- Proton-proton collider
- \( E_{\text{COM}} = 14 \text{ TeV} \)
- \( \sim 10^7 \) to \( 10^9 \) top quarks / year
- Probes \( m \sim 100 \text{ GeV} - 1 \text{ TeV} \)

[Tevatron
- \( E_{\text{COM}} = 2 \text{ TeV} \)
- \( \sim 10^2 \) to \( 10^4 \) top quarks / year]

LHC Physics
- Higgs Boson
- Supersymmetry, Extra Dimensions
- Cosmology
COSMOLOGY NOW

• Remarkable agreement
  Dark Matter: 23% ± 4%
  Dark Energy: 73% ± 4%
  Baryons: 4% ± 0.4%
  Neutrinos: 2% ($\Sigma m_\nu$/eV)

• Remarkable precision

• Remarkable results
OPEN QUESTIONS

DARK MATTER

– What is its mass?
– What are its spin and other quantum numbers?
– Is it absolutely stable?
– What is the symmetry origin of the dark matter particle?
– Is dark matter composed of one particle species or many?
– How and when was it produced?
– Why does $\Omega_{DM}$ have the observed value?
– What was its role in structure formation?
– How is dark matter distributed now?

DARK ENERGY

– What is it?
– Why not $\Omega_\Lambda \sim 10^{120}$?
– Why not $\Omega_\Lambda = 0$?
– Does it evolve?

BARYONS

– Why not $\Omega_B \approx 0$?
– Related to neutrinos, leptonic CP violation?
– Where are all the baryons?
THE DARK UNIVERSE

The problems appear to be completely different

**DARK MATTER**
- No known particles contribute
- Probably tied to $M_{\text{weak}} \sim 100$ GeV
- Several compelling solutions

**DARK ENERGY**
- All known particles contribute
- Probably tied to $M_{\text{Planck}} \sim 10^{19}$ GeV
- No compelling solutions
DARK MATTER

Known DM properties

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

Unambiguous evidence for new physics
DARK MATTER CANDIDATES

• The observational constraints are no match for the creativity of theorists

• Candidates: primodial black holes, axions, warm gravitinos, neutralinos, sterile neutrinos, Kaluza-Klein particles, Q balls, wimpzillas, superWIMPs, self-interacting particles, self-annihilating particles, fuzzy dark matter,…

• Masses and interaction strengths span many, many orders of magnitude, but not all candidates are equally motivated
NEW PARTICLES AND NATURALNESS

\[ m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 \]

\[ m_h \sim 100 \text{ GeV}, \quad \Lambda \sim 10^{19} \text{ GeV} \rightarrow \text{cancellation of 1 part in } 10^{34} \]

At \sim 100 \text{ GeV we expect new particles:}

supersymmetry, extra dimensions, something!
THE WIMP “MIRACLE”

(1) Assume a new (heavy) particle $\chi$ is initially in thermal equilibrium:

\[ \chi \chi \leftrightarrow \bar{f} f \]

(2) Universe cools:

\[ \chi \chi \leftrightarrow \bar{f} f \]

(3) $\chi$s “freeze out”:

\[ \chi \chi \not\leftrightarrow \bar{f} f \]

Zeldovich et al. (1960s)
• The amount of dark matter left over is inversely proportional to the annihilation cross section:

\[ \Omega_{DM} \sim \langle \sigma_A v \rangle^{-1} \]

• What is the constant of proportionality?

• Impose a natural relation:

\[ \sigma_A = k \alpha^2 / m^2 , \text{ so } \Omega_{DM} \sim m^2 \]

Remarkable “coincidence”: \( \Omega_{DM} \sim 0.1 \) for \( m \sim 100 \text{ GeV} - 1 \text{ TeV} \)
STABILITY

• This all assumes that the new particle is stable.

• Why should it be?
PRECISION CONSTRAINTS

- Problem: Large Electron Positron Collider, 1989-2000, provided precision constraints on new particles


- Dark Matter is easier to explain than no dark matter.
PROLIFERATION OF WIMPS

The WIMP paradigm is thriving.
Examples:

- **Supersymmetry**
  - R-parity $\rightarrow$ Neutralino DM
    Goldberg (1983); Ellis et al. (1984)

- **Universal Extra Dimensions**
  - KK-parity $\rightarrow$ Kaluza-Klein DM
    Servant, Tait (2002); Cheng, Feng, Matchev (2002)

- **Branes**
  - Brane-parity $\rightarrow$ Branon DM
    Cembranos, Dobado, Maroto (2003)

- **Little Higgs**
  - T-parity $\rightarrow$ T-odd DM
    Cheng, Low (2003)
WIMPS FROM SUPERSYMMETRY

Goldberg (1983); Ellis et al. (1983)

Supersymmetry: many motivations. For every known particle $X$, predicts a partner particle $\tilde{X}$

Neutralino $\chi \in (\tilde{\gamma}, \tilde{Z}, \tilde{H}_u, \tilde{H}_d)$

In many models, $\chi$ is the lightest supersymmetric particle, stable, neutral, weakly-interacting, mass $\sim 100$ GeV. All the right properties for WIMP dark matter.
MINIMAL SUPERGRAVITY

Co-annihilation region

Bulk region

Focus point region

Too much dark matter

Yellow: pre-WMAP
Red: post-WMAP

LHC will discover SUSY in this entire region with 1 year’s data
WHAT THEN?

• What LHC actually sees:
  – E.g., $\tilde{q}\tilde{q}$ pair production
  – Each $\tilde{q} \rightarrow$ neutralino $\chi$
  – 2 $\chi$’s escape detector
  – missing momentum

• This is not the discovery of dark matter
  – Lifetime $> 10^{-7}$ s $\rightarrow 10^{17}$ s?
THE EXAMPLE OF BBN

- Nuclear physics $\rightarrow$ light element abundance predictions
- Compare to light element abundance observations
- Agreement $\rightarrow$ we understand the universe back to $T \sim 1 \text{ MeV}$, $t \sim 1 \text{ sec}$
DARK MATTER ANALOGUE

- Particle physics $\rightarrow$ dark matter abundance prediction
- Compare to dark matter abundance observation
- How well can we do?
Contributions to Neutralino WIMP Annihilation

Jungman, Kamionkowski, Griest (1995)
• Masses can be measured by reconstructing the decay chains

\[
\begin{align*}
(m_{qR}^2)_{\text{edge}} & = \frac{(m_{\tilde{q}_2}^2 - m_{iR}^2)(m_{iR}^2 - m_{\tilde{q}_1}^2)}{m_{iR}^2} \\
(m_{qL}^2)_{\text{edge}} & = \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{q}_2}^2)(m_{\tilde{q}_2}^2 - m_{\tilde{q}_1}^2)}{m_{\tilde{q}_2}^2} \\
(m_{qL}^2)_{\text{min}} & = \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{q}_2}^2)(m_{\tilde{q}_2}^2 - m_{iR}^2)}{m_{\tilde{q}_2}^2} \\
(m_{qL}^2)_{\text{max}} & = \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{q}_2}^2)(m_{iR}^2 - m_{\tilde{q}_1}^2)}{m_{iR}^2} \\
(m_{qR}^2)_{\text{thres}} & = \frac{[(m_{\tilde{q}_L}^2 + m_{\tilde{q}_2}^2)(m_{\tilde{q}_2}^2 - m_{iR}^2)(m_{iR}^2 - m_{\tilde{q}_1}^2) - (m_{\tilde{q}_L}^2 - m_{\tilde{q}_2}^2)\sqrt{(m_{\tilde{q}_2}^2 + m_{iR}^2)^2 - 16m_{\tilde{q}_2}^2m_{iR}^2m_{\tilde{q}_1}^2} - 2m_{iR}^2(m_{\tilde{q}_2}^2 - m_{\tilde{q}_1}^2)]}{4m_{iR}^2m_{\tilde{q}_2}^2}
\end{align*}
\]
PRECISION SUSY @ ILC

- Collides $e^+e^-$
- Variable beam energies
- Polarizable $e^-$ beam
- Starts 20??
RELIC DENSITY DETERMINATIONS

% level comparison of predicted $\Omega_{\text{collider}}$ with observed $\Omega_{\text{cosmo}}$

12 July 07

Feng 24
IDENTIFYING DARK MATTER

Congratulations!
You’ve discovered the identity of dark matter and extended our understanding of the Universe to $T=10$ GeV, $t=1$ ns (Cf. BBN at $T=1$ MeV, $t=1$ s)

Are $\Omega_{\text{collider}}$ and $\Omega_{\text{cosmo}}$ identical?

Yes

Did you make a mistake?

Yes

No

Calculate the new $\Omega_{\text{hep}}$

Which is bigger?

$\Omega_{\text{cosmo}}$

$\Omega_{\text{collider}}$

Yes

No

Can you discover another particle that contributes to DM?

Yes

No

Can you identify a source of entropy production?

Yes

No

Can this be resolved with some non-standard cosmology?

Yes

No

Does it account for the rest of DM?

Yes

No

Think about dark energy

Are you sure?

Yes

No

Yes

No

Does it decay?

No

Yes

No

No

Think about dark energy
DARK ENERGY

- Freezeout provides a window on the very early universe:

\[ \frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[ n^2 - n_{eq}^2 \right] \]

Dilution from expansion

- Probe Friedmann at \( T \sim 10 \text{ GeV} \):

\[ H^2 = \frac{8\pi G_N}{3} (\rho + \Delta \rho), \quad \Delta \rho \propto T^n \]

\( n = 0 \) to 8: cosmological constant, tracking dark energy, quintessence, varying \( G_N \), ...

Drees, Iminnyayz, Kakizaki (2007)
Chung, Everett, Kong, Matchev (2007)
DIRECT DETECTION

- **WIMP properties:**
  \[ v \sim 10^{-3} \, c \]
  Kinetic energy \( \sim 100 \, \text{keV} \)
  Local density \( \sim 1 / \text{liter} \)

- Detected by recoils off ultra-sensitive underground detectors
DIRECT DETECTION IMPLICATIONS

LHC + ILC $\rightarrow$ $\Delta m < 1$ GeV, $\Delta \sigma/\sigma < 20\%$

Comparison tells us about local dark matter density and velocity profiles, ushers in the age of neutralino astronomy.
INDIRECT DETECTION IMPLICATIONS

COLLIDERS ELIMINATE PARTICLE PHYSICS UNCERTAINTIES, ALLOW ONE TO PROBE ASTROPHYSICAL DISTRIBUTIONS

\[ \frac{d\Phi_\gamma}{d\Omega dE} = \sum_i \frac{dN_i^\gamma}{dE} \sigma_i v \frac{1}{4\pi m_{\chi}^2} \int_\psi \rho^2 dl \]

Very sensitive to halo profiles near the galactic center

Particle Physics       Astrophysics

12 July 07  Feng 29
TAKING STOCK

• WIMPs are astrophysically identical
  – Weakly-interacting
  – Cold
  – Stable

• Is this true of all DM candidates?

• No. But is this true of all DM candidates independently motivated by particle physics and the “WIMP miracle”?

• No! SuperWIMPs: identical motivations, but qualitatively different implications
SUPERWIMPS: BASIC IDEA

Feng, Rajaraman, Takayama (2003)

Supersymmetry: Graviton $\rightarrow$ Gravitino $\tilde{G}$
Mass $\sim 100$ GeV; Interactions: only gravitational (superweak)

- $\tilde{G}$ not LSP

- Assumption of most of literature

- $\tilde{G}$ LSP

- Completely different cosmology and particle physics
SUPERWIMP RELICS

- Suppose gravitinos $\tilde{G}$ are the LSP
- WIMPs freeze out as usual
- But then all WIMPs decay to gravitinos after $M_{Pl}^2/M_W^3 \sim$ seconds to months

Gravitinos naturally inherit the right density, but interact only gravitationally – they are superWIMPs (also KK gravitons, quintessinos, axinos, etc.)

Feng, Rajaraman, Takayama (2003); Bi, Li, Zhang (2003); Ellis, Olive, Santoso, Spanos (2003); Wang, Yang (2004); Feng, Su, Takayama (2004); Buchmuller, Hamaguchi, Ratz, Yanagida (2004); Roszkowski, Ruiz de Austri, Choi (2004); Brandenburg, Covi, Hamaguchi, Roszkowski, Steffen (2005); …
Charged Particle Trapping

- SuperWIMPs are produced by decays of metastable particles. These can be charged.

- Charged metastable particles will be obvious at colliders, can be trapped and moved to a quiet environment to study their decays.

- Can catch 1000 per year in a 1m thick water tank

Feng, Smith (2004)
De Roeck et al. (2005)
IMPLICATIONS FROM CHARGED PARTICLE DECAYS

\[ \tau (\tilde{l} \rightarrow l \tilde{G}) = \frac{6}{G_N} \frac{m_{\tilde{G}}^2}{m_l^5} \left[ 1 - \frac{m_{\tilde{G}}^2}{m_l^2} \right]^{-4} \]

- Measurement of \( \tau \), \( m_l \) and \( E_\ell \rightarrow m_{\tilde{G}} \) and \( G_N \)
  - Probes gravity in a particle physics experiment!
  - Measurement of \( G_N \) on fundamental particle scale
  - Precise test of supergravity: gravitino is graviton partner
  - Determines \( \Omega_{\tilde{G}} \): SuperWIMP contribution to dark matter
  - Determines \( F \): supersymmetry breaking scale, contribution of SUSY breaking to dark energy, cosmological constant

Hamaguchi et al. (2004); Takayama et al. (2004)
SUPERWIMP COSMOLOGY

Late decays can modify BBN
(Resolve $^7\text{Li}$ problem?)

Late decays can modify CMB
black body spectrum
($\mu$ distortions)

Fields, Sarkar, PDG (2002)

Fixsen et al. (1996)
SMALL SCALE STRUCTURE

- SuperWIMPs are produced in late decays with large velocity \((0.1c – c)\)

- Suppresses small scale structure, as determined by \(\lambda_{FS}, Q\)

- Warm DM with cold DM pedigree

Dalcanton, Hogan (2000)
Lin, Huang, Zhang, Brandenberger (2001)
Sigurdson, Kamionkowski (2003)
Profumo, Sigurdson, Ullio, Kamionkowski (2004)
Kaplinghat (2005)
Cembranos, Feng, Rajaraman, Takayama (2005)
Strigari, Kaplinghat, Bullock (2006)
Bringmann, Borzumati, Ullio (2006)
CONCLUSIONS

• Particle Dark Matter
  – As well-motivated as ever
  – WIMPs: Proliferation of candidates
  – SuperWIMPs: Qualitatively new possibilities (warm, metastable, only gravitationally interacting)

• If dark matter is WIMPs or superWIMPs, colliders
  – will produce it
  – may identify it as dark matter
  – may open up a window on the universe at $t \sim 1 \text{ ns}$

• LHC begins in July 2008 – this field will be transformed by GRG19